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PHASE LOCKING OF TWO HIQ RESONATORS

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The experimental results of phase locking two confocal unstable resonators with 90° beam rotation (UR90 or HiQ) are presented. The two resonators used separate gain cells located in different rooms. The lasers were conventionally coupled by passing a portion of the reverse wave from each laser through a hole in the wall and injecting it into the other laser's forward wave. The roles of self-feedback and alignment sensitivity in phase-locking are examined.

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PREFACE

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INTRODUCTION

When two or more lasers of the same wavelength are coherent and in phase (phase-locked), the intensity of the central bright spot on-axis increases as the square of the number of beams being combined (Ref. 1). If, for example, three lasers are phase-locked together, the on-axis spot of the output will be nine times as intense as the on-axis spot of one of the lasers, assuming they all have roughly the same intensity. Phase locking is the objective in coupling multiple laser resonator cavities.

Different types of mechanisms can provide the necessary communication between and within cavities to phase-lock lasers (Ref. 2). When this communication is properly accomplished, light from one laser or mode should stimulate emission in the other laser or mode. Two of the mechanisms that can provide communication within a laser cavity are: self-feedback and scattering. Self-feedback in a ring laser is usually caused by inhomogeneities in the gain medium. In a gas laser, differences in pressure or gas concentrations can make a portion of the reverse-mode scatter into the forward mode. Scattering is also produced by imperfections on the surface of the mirrors and on or inside gain medium windows. If the mirror surface has any irregularities or roughness, a small fraction of the beam reflects in different directions. Some of this scattered light will reflect back into the incoming beam, and this light may couple the counterrotating modes within a cavity.

The two types of communication between laser cavities are: cross talk and adjoint coupling. Cross talk usually occurs when two or more lasers share the same gain medium or when lasers are operated with a very small distance between them. Under these circumstances, the lasers can couple by diffraction or scattering of one laser directly into the other. Adjoint coupling is forced with the use of mirrors. For a pair of ring lasers, each having a forward and reverse-mode running concurrently, adjoint coupling occurs when the reverse-mode of one laser is injected into the other laser's forward mode, and vice versa. Self-feedback, scattering, and adjoint coupling are the basic mechanisms that allowed the phase-locking of the HiQ resonators presented in this paper.

Two common ways of coupling linear cavities can easily be applied to rings. One technique, coupled resonators, consists of injecting a portion of the output from each laser into all other lasers in the system (Ref. 3). A second technique is the master-slave scheme, where the relative phases between the lasers are fixed by injecting the light from a single master oscillator into each of the other lasers (Ref. 4). In this master-slave method, the stronger laser becomes the master laser and the other lasers then adopt the same frequency and phase of the master. With two lasers, if the weaker laser is used as the master, the stronger laser can be "forced" to lase in the modes of the weaker laser from which it has received phase and frequency information. One application of such coupling combines the outputs of an array of diode lasers into a single intense laser beam. The ability to lock the phase of one laser to a second remote laser would permit the coherent processing of images transmitted through an optical fiber via nonlinear optical techniques (Ref. 5).

A coupling resonator technique for ring lasers is experimentally studied in this work. This was done with the use of a single coupling path that injects the output of each laser into the other. To couple ring lasers, the counterrotating reverse and forward modes of each laser must be coupled so that every mode of the system can reproduce itself after a complete round trip through both lasers (Ref. 6).

The ring lasers used in this study were confocal, unstable resonators with a 90-deg intracavity beam rotation which created circularly polarized light. This type of laser, known as UR90 or HiQ, has several advantages (Ref. 7). It is relatively insensitive to misalignment, and it mitigates aberrations due to variations in the gain medium or imperfect optical elements (Ref. 8). Totally reflecting optics can be employed with this device, in contrast to stable resonators, which must use partially reflecting optics. Partially reflecting output couplers, which may be necessary in high-power laser applications, cannot be easily cooled. Unstable resonators provide good transverse-mode control which is another advantage when trying to phase-lock lasers. Other features of unstable resonators are their ease of alignment and adjustment, and efficient power extraction (Ref. 9).

This report describes the phase locking of two CO_2 ring lasers with HiQ cavities using two different gain cells. The lasers were located in different rooms, and the coupling path passed through a hole in the wall separating the two laboratories. Using different gain cells eliminated the possibility that the lasers would be coupled by scattering from cavity mirrors or cross talk in the gain media. Furthermore, locating the lasers in different rooms ensured that the coupling optics provided the only phasing control. Using separate rooms with different optical tables added two more parameters to the coupling of the lasers. Different temperatures in the rooms could affect the optics dissimilarly, and vibrations in the two tables could add different amounts of jitter to the optics of each resonator.

To achieve phase locking, the reverse-mode output of each laser was injected into the other laser's forward mode by using a reverse-mode coupler mirror that changed the slightly diverging output of the reverse-mode into a slightly converging input. This converging wave is propagated in the direction of the forward mode of the receiving laser. When the coupling leg was properly aligned, the lasers were phase-locked.

To demonstrate that phase locking occurred, the two forward mode outputs of the lasers were interfered with, and the visibility of the resulting fringes was measured. Obtaining a fringe pattern demonstrated that both beams had the same phase, and therefore, the two lasers were phase-locked. After the lasers had been phase-locked, the effect of suppressing intracavity backscatter was studied. This scattered light may provide the coupling of the counterrotating modes within a particular resonator. The main source of this backscattering was the gain cell windows. Also studied was the effect of using mirrors to enhance the coupling of the counterrotating modes in each laser. Small injection mirrors were placed normal to the optic axis and in the path of the reverse-mode beam of each laser. This portion of the reverse-mode was reflected into the forward mode to help couple the forward and reverse-modes. Other conditions such as the size of the laser-to-laser coupler and misalignment sensitivity, were also studied. An iris was placed in front of the laser-to-laser coupling mirror to study the amount of coupling needed to achieve phase locking. Misalignment sensitivity was measured by tilting the concave mirror in the beam-expanding telescope.

COUPLING CONDITIONS

Se eral conditions must be met in order to couple resonators. Both lasers must have the same polarization, and the modes generated in one cavity must be able to propagate a full round trip through both cavities (Ref. 3). The selection of the appropriate coupler mirror is also a major factor in good phase locking.

POLARIZATION

The lasers used in this experiment were circularly polarized, and the polarization direction direction depended on the way in which the roof mirrors were arranged (Ref. 6). The polarization was rotated by the same angle as the beam. The roof mirrors were arranged so that the polarizations of each laser were polarized in the same sense.

FREQUENCY

Having both lasers operate at the same frequency and with the same transverse-modes simplified the phase-locking process. Single-frequency operation was obtained by using a homogeneously broadened gain media. The laser had a pulse of 1 ms, which gave sufficient time for the laser to stabilize into a single mode. Due to the nature of the CO_2 molecule and its transitions, and to the fact that both cavities were the same, it is safe to assume that the lasers were operating at the strongest operating frequency of 10.5915 μm (Ref. 10).

FRESNEL NUMBER

To obtain the same transverse-mode was more complicated. Single-transverse-mode operation was obtained by the selection of the correct equivalent Fresnel number (Ref. 11). Excellent transverse-mode discrimination is obtained in the vicinity of $N_{eq} = 0.38$, which is at one of the dominant mode peaks (or loss minima). These maxima occur at every successive integer-plus-five-eights value of N_{eq}. This is also where the diffraction loss is substantially less than that predicted by the geometrical optics approximation and as verified experimentally (Ref. 12). The Fresnel number for a HiQ resonator is given by (Ref. 13)

$$N_{eq} = \frac{a^2\left(M^2 - 1\right)}{2\lambda\left(M^2 L_a + M L_b + L_c\right)} \qquad (1)$$

where a is the radius of the concave mirror, M is the magnification, λ is the wavelength of the laser, and L_a, L_b, and L_c are lengths of the sections of the resonator in a strip-resonator representation (Fig. 1).

REVERSE-MODE COUPLER

In order to couple all modes from the system, both counterrotating modes in each laser must first be coupled, and then the modes between lasers must be coupled (Ref. 3). Self-feedback from the gain medium and backscattering from mirrors and cell windows was sufficient to establish coherence between the counterrotating modes (Ref. 14). Coupling from laser to laser was done conventionally by the use of mirrors. A main coupler mirror and beam steering optics were used to direct the beams from the room where the first laser was located, through a hole in the wall, and into the other room where the second laser was located. The coupler mirror is referred to as the reverse-mode coupler because it utilized the outputs of the reverse-mode clippers from both lasers.

The reverse-mode coupler mirror used in this experiment replaced a reverse-mode suppressor in a single HiQ resonator, but instead of being used to suppress the reverse-mode beam, it was used to couple the lasers. The beam, after being reflected from the reverse-mode coupler, entered the second laser in its forward direction. A reverse-mode suppressor mirror must reflect a beam with twice the radius of curvature of the forward converging wave (Ref. 6). The case of the HiQ resonator was of particular interest because the forward mode is a collimated wave while the reverse mode diverges. The reverse-mode radius of curvature was calculated by Paxton and was found by using the reverse-mode system matrix (Ref. 8):

$$S = \begin{bmatrix} 1/M & ML_a+L_b+L_c/M \\ 0 & M \end{bmatrix} \qquad (2)$$

Using the round-trip matrix equation:

$$\begin{bmatrix} r \\ r' \end{bmatrix} = S \begin{bmatrix} r_0 \\ r'_0 \end{bmatrix} \qquad (3)$$

where r_0 is the ray entering the system, and r'_0 is the slope of this ray; r is the ray leaving the system, and r' is the slope of this ray. The radius of curvature is obtained from $r' = nr/R$, and with the index of refraction $n = 1$ the radius of curvature becomes $R = r/r'$. Because the wave replicates itself after a round trip, $R = r/r' = r_0/r'_0$. The reverse-mode round-trip equation becomes

$$\begin{bmatrix} r \\ r/R \end{bmatrix} = \begin{bmatrix} 1/M & ML_a + L_b + L_c/M \\ 0 & M \end{bmatrix} \begin{bmatrix} r_0 \\ r_0/R \end{bmatrix} \tag{4}$$

Solving these two equations:

$$R_{reverse} = \frac{M^2 L_a + M L_b + L_c}{M^2 - 1} \tag{5}$$

$R_{reverse}$ is the radius of curvature of the forward converging wave entering the laser; therefore the radius of curvature of the reverse-mode coupler, R_{rmc}, is

$$R_{rmc} = 2 \times R_{reverse} \tag{6}$$

The equations give R_{rmc} as a function of length. A mirror with a specific radius of curvature R_{rmc} was not available, so it was necessary to control the length of the resonator to match the curvature. With this in mind, and a magnification of 1.25, the resonator was set up to have L_a = 6.930 m, L_b = 1.816 m, and L_c = 2.014 m. This allowed the use of a mirror with a radius of curvature of 43.9 m for the coupling optic.

LAYOUT

LAYOUTS OF INDIVIDUAL HIQ RESONATORS

The layouts for the two resonators used in this project are shown in Figures 2 and 3. The HiQ resonator layout was first presented by Holswade et al (Ref. 15). Each rooftop mirror (RM1, RM2) consisted of two circular flat mirrors with a diameter of 15.2 cm and a flatness $\leq \lambda/30$ at 10.6 μm. They were mounted orthogonally, and then the mirror assemblies were rotated by 45 deg to the horizontal about an axis parallel to the optic axis at the clipper plane. These rooftop mirrors rotated the rectangular beam by 90 deg, lifted it out of the plane formed by the turning flats and concave mirror, and translated it horizontally. After rotation by the rooftop mirrors, the output was clipped by the forward-mode clipper mirrors (C1, C3). The reverse-mode clipper mirrors (C2, C4) were located in the same place as the forward-mode clippers but facing in the opposite direction. The beam was then expanded by the convex mirrors (M2, M6) and recollimated by the concave mirrors (M1, M5), completing a round trip of the ring. The clippers and convex mirrors were mounted above the plane formed by the other components. A feedback beam passing the clippers and coming into the ring again for another round trip was expanded back to its original dimensions by the convex mirror. This beam was translated down on its way to the concave mirror where it was recollimated and then passed through the gain cell. The beams were directed back through the gain cells by the turning flats (M3, M4, M7, & M8) and onto the rooftop mirrors (RM1, RM2) which rotated the beam 90 deg and translated it back to the level of the clippers.

All the beam-steering optics, except the rooftop mirror assemblies, had surface figures of better than $\lambda/50$ peak-to-valley at 10.6 μm. Each of the telescopes had a magnification of $M = 1.25$.

LAYOUT OF THE PHASE-LOCKED SYSTEM

The layout of the two resonators together is presented in Figure 4. Of the optics used to couple the lasers together, only the reverse-mode coupler (M9) is shown in the figure. The beam-steering optics used to translate the beams to the reverse-mode coupler are not shown because they do not affect the performance in any way except for minor losses. The reverse-mode coupler was located in the same room as the ARTS cell (discussed below). The paths from the reverse-mode clippers of each laser to the reverse-mode coupler mirror were made equal in length by directing the beam from HiQ #1 (ARTS cell) down the optical table and back. The beam from HiQ #2 was directed through the hole in the wall and to the reverse-mode coupler.

GAIN CELLS

Gain was provided by the Weapons Laboratory's Advanced Resonator Test System (ARTS) and Mini Advanced Resonator Test System (MARTS) (Ref. 16). ARTS consisted of an isolated 30.5-cm-diam CO_2 laser gain cell (10.6 μm) operated at 3.5 torr. The gas mixture flowed through the cell at 2700 ft^3/min. A partial pressure ratio of 4:1:1 (helium, nitrogen, and carbon dioxide) was used. The gases were cooled to -10°C at the inlet to the cell. A 17,000-V discharge with a 2.5-A, square current pulse of 1-ms duration was used. A maximum pulse rate of 10 pulses/s was used to excite the gas mixture. Due to the electrode placement, the highest gain was found near the cell walls. This value decreased to slightly less than half of the peak gain at the center of the cell. MARTS operated with the same parameters as ARTS but had only a 15.2-cm diameter.

ALIGNMENT

ALIGNMENT OF HiQ RESONATOR

The method followed to align each of the individual resonators was that used by Holswade et al (Ref. 7). The telescope mirrors were positioned with the help of a collimated beam from a Fizeau interferometer. A system of masks placed at the ends of the gain cell cut the beam to the size of the actual intracavity mode, and the interferometer beam was injected into the resonator by turning flats. This showed where the intracavity mode would exist and allowed the telescopic optics to be positioned as close to on-axis as possible without vignetting the beam. The rest of the optics were then aligned with the use of a standard HeNe pellicle alignment technique. In this alignment, masks with small holes along the optical axis were placed on both sides of the gain cell, and these masks were removed after the initial alignment. To "fine tune" the laser the concave telescope mirror was adjusted slightly after all the optics were in place. These adjustments were made while watching the near-field output of the laser with an infrared (IR) camera. The laser was deemed to be aligned when the best near-field output pattern was obtained. The best near-field output pattern was one which had both uniform intensity and the same dimensions as that of the clipper obscuring the beam path.

ALIGNMENT OF REVERSE-MODE COUPLER

The next step was the alignment of the reverse-mode coupler mirror. An odd number of beam-steering mirrors had to be used between the reverse-mode clipper of one laser and the reverse-mode clipper of the other laser in order to preserve the correct circular polarization "handedness" of the coupled resonator system. If, for instance, the light coming from the reverse-mode clipper were directed straight to the reverse-mode coupler, the polarization of the reflected light would change handedness. So if the forward mode in each laser were right-circular polarized and the reverse-mode left-circular polarized, after the reverse-mode was reflected from the coupler mirror it would enter the forward mode of the other laser with the desired polarization. This would also be true after three, five, or any odd number of reflections.

Since in this experiment the lasers were in separate rooms, seven mirrors were needed to direct the beam exiting the reverse-mode clipper to the other laser's reverse-mode clipper. For coarse alignment of the coupler mirror, the beams coming out of the reverse-mode clippers were traced through each other's paths into the opposite laser by using heat-sensitive, liquid-crystal paper. After each beam was traced back into the other, the outputs of the forward mode of the lasers were combined by the use of a beam splitter, and the actual fine alignment of the reverse-mode coupler was made. By looking at the forward output with an infrared camera, the reverse-mode mirror was adjusted to achieve the fringes with the highest visibility.

PHASE-LOCKING RESULTS

FORWARD-TO-REVERSE-MODE COUPLING

In order to couple N lasers, light from each laser must be injected into the other N-1 lasers. This sharing ensures that they will be running in the same mode. Additionally, for ring lasers the forward and reverse-mode are not necessarily coherent with each other. The forward and reverse-mode of each laser must be coupled together so that every mode of the coupled system will be able to reproduce itself after a complete round trip through the system (Ref. 6). Therefore, light injected into any laser from another laser can return to the original laser.

Intracavity Backscattering

Intracavity coherence is established by the backscattering of one mode into the other counterrotating mode (Ref. 14). Most of this backscattering is due to imperfect mirror surfaces and reflections from the gain medium windows. In the case under consideration, the mirrors used were better than 99 percent reflective at 10.6 μm, and none of them was normal to the optic axis. Most of the radiation not reflected by the mirrors was absorbed (Ref. 9). On the other hand, the zinc selenide windows at the end of the gain medium, even though they were 98.8 percent reflective, were oriented perpendicular to the optic axis. This made specular reflections possible and directed a great part of the scattered light back into the resonator. The main source of backscattering in this system was the zinc selenide windows.

Backscattering Suppression

Before the experiment was completed, it was suggested that the greatest factor contributing to coupling the lasers' counterrotating modes was this backscattering and specular reflections from the gain medium windows. In high power lasers it is common to use aero-windows which produce minimum backscattering (Ref. 2). It was thought that, for such high-power lasers, forward-to-reverse-mode coupler mirrors were needed to achieve phase locking. The backscatter from the windows of the lasers in this study was suppressed to prove that a significant amount of backscattering is not necessary to lock the counterrotating mode.

Four steps were taken to suppress the backscattering and the specular reflections from the windows. First, the windows were AR-coated for 10.6 μm. Second, a metal ring with a wedge of 1.6 deg was placed between the gain cell and the windows in the MiniARTS cell. This wedge caused a 1.6-deg angle of incidence for the windows. The transmission of the window with 10.6-μm light at 1.6-deg angle of incidence was measured at 98.8 percent. The combination of a low reflectivity and adjustment of the window angles not only eliminated the effect of specular reflections, but also should have suppressed the backscatter to an insignificant amount. At this time the coupler mirror was properly aligned and coupling was achieved easily, indicating that the forward and reverse-modes were also coupled.

The third step was to rotate the ARTS cell used in the HiQ #2 resonator so that it would not be perpendicular to the optic axis of the laser. Placing the cell at an angle creates the same effect of the ring wedge in the other cell (see Fig. 5). The new beam train was located at an angle of 2.3 deg with respect to the normal. At this angle, the transmission of the window was measured at 98.8 percent. As with the first cell, the combination of the angle of incidence and a low reflectivity should have suppressed the backscatter. After the coupler mirror was properly aligned, coupling of the lasers was again achieved easily, indicating that there was still coupling between the counterrotating modes of each laser.

The last step taken to suppress backscatter was the use of masks which limited the path of the beams. The size of the beam coming into the telescope was 4.1 × 3.5 cm, and the size of the masks used was 6.8 × 5.4 cm. The beam coming out of the telescope was 4.1 × 5.2 cm and the mask size was 6.8 × 7.1 cm. The masks were slightly larger than the beam outline to allow for the expanded reverse-mode beam coming from the coupler mirror (Ref. 17). A comparison of the beam size to mask size can be seen in Figure 6.

Visibility Measurement

After the above steps were taken to suppress backscatter, phase locking of the lasers was somewhat harder to achieve. The coupler mirror had to be aligned with greater precision, because even minor deviation made the beams walk off the optical axis and intercept the masks. However, phase locking was still observed. This demonstrated that a large amount of backscatter is not necessary to couple the counterrotating modes. This statement holds as long as the frequencies of the forward and reverse modes are well within the locking range (Ref. 2). The farther the frequencies are from each other, the more backscatter is necessary to ensure coupling between the modes.

To obtain a qualitative measurement of how well the two lasers were coupled, the fringe pattern created by the combined output of the lasers was examined. An IR camera and a video frame grabber were used to photograph the fringes (Fig. 7a). A fast scanning mirror was also used to scan the fringes across a detector to obtain a profile of the fringe pattern for quantitative analysis. This is depicted in Figure 7b. With this profile, a measure of the visibility of the fringe pattern could be obtained, where visibility is defined as

$$\text{Visibility} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{7}$$

After the backscatter suppression steps were taken, the visibility was about 0.79, which was still very good. The highest visibility theoretically possible is unity, which occurs only when the lasers are both phase-locked and have exactly the same output intensity.

Note that when the lasers were coupled not every shot produced fringes. A system was considered to be phase-locked when the interference of the two lasers produced a fringe pattern. Even if fringes were seen only one out of every five pulses (20 percent of the time), this could still be considered coupling to some extent. The reasons for the low coupling rates are discussed in the section on the source of errors.

Injection Mirrors

In the preceding two sections, the effect of suppressing the backscatter was studied. It was determined that, even after the backscatter from the windows was suppressed, the counterrotating modes were coupled, though the phase locking rate diminished slightly. This reduction in phase-locking rate was due to a more restricted locking range between the forward and reverse-modes. These results led to an expectation of a higher phase-locking rate if forward-to-reverse-mode coupling were enhanced. The counterrotating mode coupling was maximized by the use of small injection mirrors in the path of the reverse-mode beam (see Fig. 8). The mirrors were aligned so that the reflection from them went back into the forward mode of the same laser it had come from, coupling forward and reverse-modes together more efficiently. Alignment of the mirrors was done by using heat-sensitive liquid crystal paper and by observing the images of the near-field laser patterns with an IR camera. The heat-sensitive liquid-crystal helped to direct the reflection of the mirrors parallel to the beam again. The IR camera allowed fine adjustment. Any improvement of the fringe pattern because of enhancement in the forward-to-reverse-mode coupling could also be observed. A comparison with the earlier case which did not enhance the counterrotating mode coupling was done by blocking the injection mirrors with a piece of paper. Blocking was not as ideal as removing the mirrors, because the mirrors still obscured a portion of the path of the reverse-mode beam. Blocking was used due to the difficulty in aligning the mirrors identically each time one was removed. Additionally, blocking ensured consistency in mirror location. A tally of the pulses in which fringes could be seen was taken to evaluate quantitatively the effect of these mirrors in phase locking the lasers. One hundred pulses were watched in each case. Two individuals observed the fringe pattern and counted the pulses. The two individuals were used because the observance of fringes was somewhat subjective. A good fringe pattern should exhibit enough contrast between dark and bright sections of the beam so that separate lines can be identified. The ratio of fringe occurring using the injection mirrors to that occurring without mirrors was approximately 3:1. Even though the injection mirrors were not essential to couple the counterrotating modes and achieve phase-locking, they did help to increase the rate of phase-locking.

LASER-TO-LASER COUPLING

Reverse-Mode Coupler Size

An increase in the phase-locking rate of the lasers was observed due to enhanced coupling of the counterrotating modes. In the same manner, one might also expect a change in the phase-locking rate with a change in laser-to-laser coupling. This was demonstrated by changing the size of the reverse-mode coupler beam. The size of the beam was changed by placing an iris in front of the coupler mirror. The size of the iris was reduced to determine the minimum aperture for which a fringe pattern could still be observed with the IR camera. This was done in steps, and two counts of the phase-locked pulses were taken at each aperture size, one with the injection mirrors blocked and one unblocked. The results of this comparison are presented in Figures 9 and 10. Two individuals observed the fringe pattern and counted the pulses. The smallest aperture in which a good fringe pattern could still be observed was 0.8-cm diameter, or an area of 0.49 cm^2. At this size, fringes were seen once every few pulses, a rate of around 12 percent.

Minimum Reverse-Mode Coupling

The minimum reverse-mode coupling needed to observe phase-locking can be calculated using the minimum size of the aperture and the size of the reverse-mode beam coming from the clippers. The reverse-mode beams coming from the MiniARTS and ARTS cells were measured as 1.05 cm^2 and 0.52 cm^2, respectively. The minimum size of the aperture was 0.49 cm^2. The reverse-mode beam utilized to observe coupling was 46 percent of the reverse mode of one laser and 95 percent of the reverse mode of the other laser. The fact that 95 percent of the area of the beam in relation to the aperture was used to couple the lasers together does not necessarily mean that 95 percent of the power was needed. There are two factors that need to be considered. First, the estimate of the beam size utilized does not take into consideration the reverse-mode beam's irregular shape, nor the iris' circular shape. This resulted in a higher estimate by 10 to 20 percent for the case of the smaller reverse-mode beam. The aperture matched the size of this beam closely. An irregularly shaped beam was more apt to "miss" the aperture than a beam significantly larger than the aperture. Another factor to consider is that one of the lasers could be dominant and act as a master oscillator. Several factors could have determined which of the lasers would dominate, and could in fact have changed from pulse to pulse. Among these factors were the intensity of the beam and the alignment of the lasers. For this experiment it is safe to assume that, most of the time, the laser utilizing the MiniARTS cell would be the dominant laser. This laser possessed a stronger output and better beam shape most of the time. The reverse-mode beam of this laser was also stronger.

Taking these two major factors into consideration, the smaller beam estimate was reduced by 10 to 20 percent. Averaging this result with the larger beam estimate showed that 60 to 65 percent of reverse-mode coupling was needed to achieve phase-locking.

MISALIGNMENT SENSITIVITY

The sensitivity of the coupled ring lasers to coupling path alignment was determined by measuring the visibility of the near-field fringe pattern of the phase-locked lasers at different orientations of the reverse-mode coupler mirror. This method provided a more direct assessment of the quality of the fringes than the 100-pulses-count method used before. The reverse-mode coupler mirror was rotated from side-to-side until the visibility reached a value of zero. Although the quality of the fringes deteriorated and the rate diminished while the orientation of the reverse-mode coupler was changing, fringes seen showed that the lasers were still phase-locked to some extent. The visibility reached a value of zero at 4 arc sec of misalignment from center to each side (see Fig. 11).

SOURCE OF ERRORS

One major problem encountered was trying to match the amplitude of both resonators. Due to the way the ARTS and Mini ARTS systems worked, the gain was always higher when closer to the walls of the cells. Because the resonator using the ARTS cell was oriented with a small angle to eliminate backscatter from the windows, most of the beam train was through the center of the cell where the gain is lower. To match the amplitudes of the lasers, an attenuation filter was placed in the output beam from the MiniARTS. The filter helped to match the outputs closely, but they were still not exactly the same. This was probably why the visibility did not get as close to unity as would have been liked.

Another problem was that the lasers were in separate rooms and consequently on separate optical tables. Any vibrations of one table affected only that specific laser. This isolation could have made the lasers walk off the locking range temporarily, affecting both the phase-locking rate and the visibility of the fringes.

Still other errors arose from other causes. The injection mirrors were in the path of the reverse-mode beam, which could have affected the phase-locking rates whether the mirrors were blocked or unblocked. However, the increase in phase-locking rates was so dramatic that the results remain significant. Eye fatigue in the individuals counting the fringe pattern pulses could have affected the results slightly, but this effect was minimum. Irregularities of the beam shape in relation to the aperture shape prevented an exact determination of the effects of changing the amount of reverse-mode beam necessary for phase locking. All these sources of errors affected some results more than others, but none of these errors was significant enough to invalidate the basic findings of this effort.

CONCLUSION

Phase-locking of two CO_2 lasers with HiQ cavities, using separate gain cells, was demonstrated for the first time. The lasers used separate gain cells and were coupled by taking the reverse-mode of each laser and injecting it in the forward mode of the other.

Although coupling of the counterrotating modes of each individual laser was needed, this occurred without the use of additional mirrors. Even after suppressing the backscattering from the windows, which helped decouple the forward and reverse-mode of each laser together, the counterrotating modes were still coupled. This is a significant result because lasers utilizing aerowindows (some high-energy lasers) do not produce backscatter. It was shown that some systems can still be coupled without additional forward-to-reverse coupler mirrors. The use of mirrors to enhance the counterrotating modes demonstrated a threefold increase in the phase-locking rate.

The misalignment sensitivity of the reverse-mode coupler mirror was measured. Even though the HiQ resonator has a low misalignment sensitivity, misaligning the reverse-mode coupler mirror made the quality of the fringes deteriorate rapidly, showing that the whole phase-locked system is very sensitive. This study demonstrated that two HiQ lasers can be phase-locked together conventionally, and showed ways of enhancing the coupling.

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APPENDIX: BASIC MODE THEORY FOR PHASE-LOCKED RESONATORS

The intent of this section is not to solve the mode equations for the phase-locked system, but to state what they are and how they relate to the results of this paper. Using the approach taken by Holswade et al, and neglecting coupling of the forward and reverse mode and laser-to-laser modes, the transverse-modes are solutions of the integral equations (Ref. 7):

$$\lambda_i F_{1i}(x,y) = K_{F_1} * F_{1i}(x,y) \tag{A1}$$

$$\lambda_j F_{2j}(x,y) = K_{F_2} * F_{2j}(x,y) \tag{A2}$$

$$\bar{\lambda}_i B_{1i}(x,y) = K_{B_1} * B_{1i}(x,y) \tag{A3}$$

$$\bar{\lambda}_j B_{2j}(x,y) = K_{B_2} * B_{2j}(x,y) \tag{A4}$$

F_{1i} defines the transverse amplitude, phase and transverse polarizations state of the field in Laser 1 for the ith mode. The same applies for the jth mode in F_{2j} in Laser 2. B_{1i} and B_{2j} are the correspondent reverse-modes. λ_i and λ_j are the feedback eigenvalues and K_F and K_B are the round-trip propagation operators for the lasers. Because both resonators have the same parameters of dimensions, magnification and wavelength we can say that:

$$K_{F_1} = K_{F_2} = K_F \tag{A5}$$

and

$$K_{B_1} = K_{B_2} = K_B \tag{A6}$$

For the case of the phase-locked system, forward and reverse modes have to propagate in the same manner; therefore we assume that $K_F = K_B = K$. For the same reason $\lambda = \bar{\lambda}$. The mode-determining equations, including coupling between the lasers and between the forward and reverse directions, generalize to the form:

$$\lambda F_1 = K * F_1 + R_+ * B_2 \tag{A7}$$

$$\lambda F_2 = K * F_2 + R_+ * B_1 \tag{A8}$$

$$\lambda B_1 = K * B_1 + R_- * F_2 \tag{A9}$$

$$\lambda B_2 = K * B_2 + R_- * F_1 \tag{A10}$$

As can be seen from these equations, for F_1 and F_2 to be coupled, the resulting output will be a function of all four modes F_1, F_2, B_1, B_2; so they all must be coupled with each other. When the lasers are phase-locked, every mode of the system can reproduce itself after a complete round trip through both lasers.

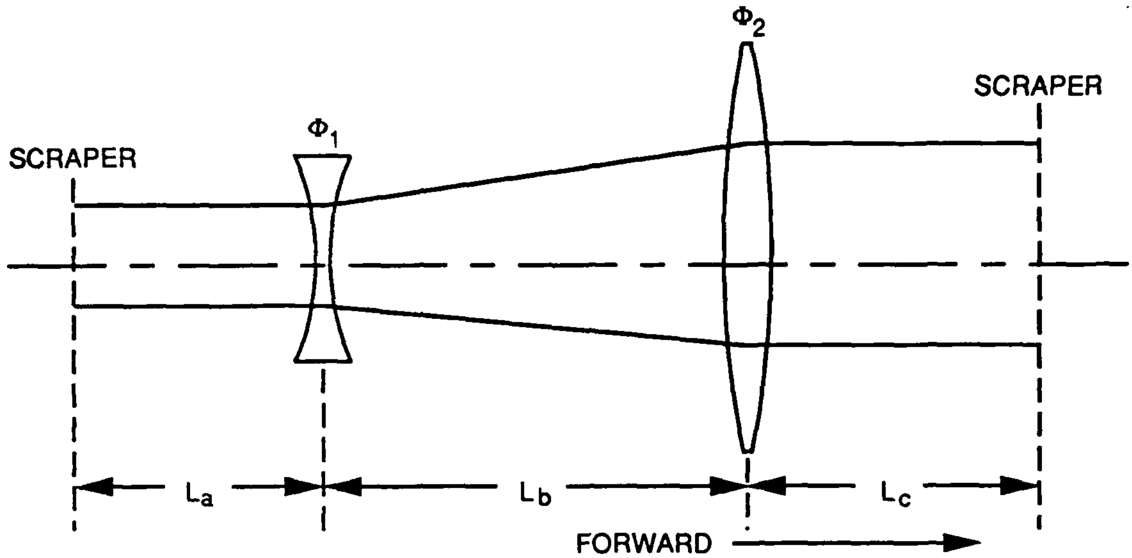


Figure 1. Strip resonator representation of HiQ.

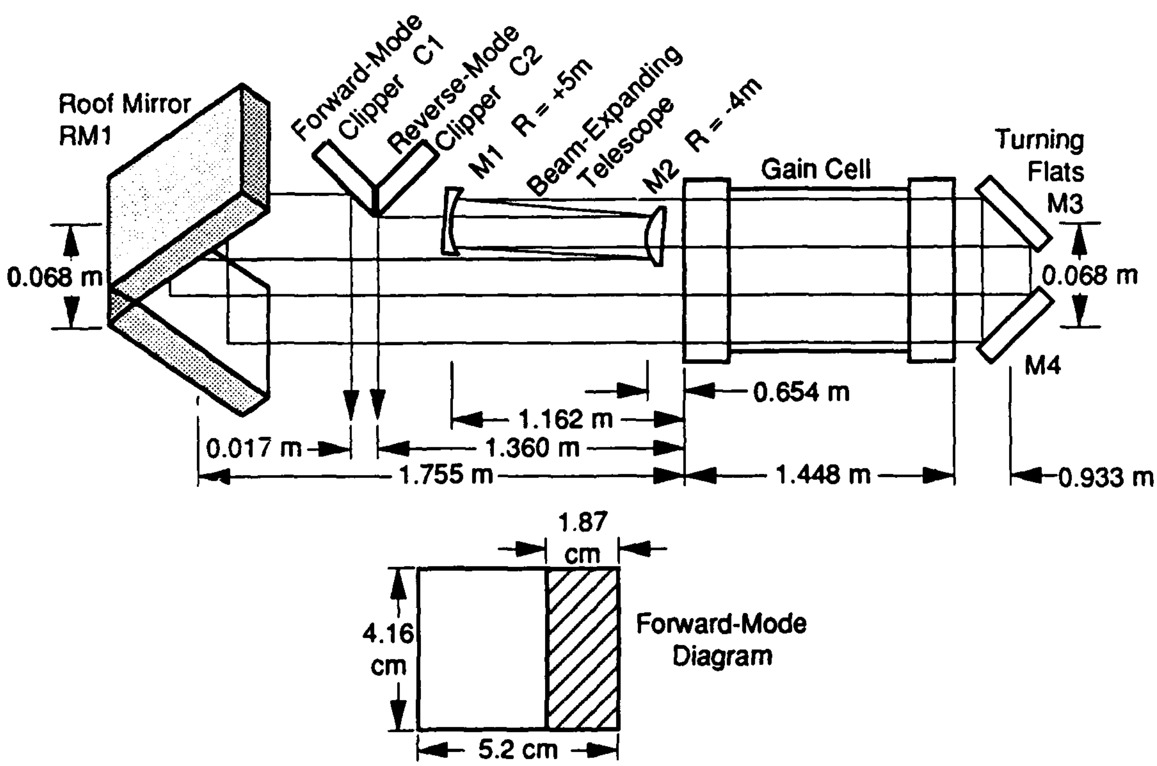


Figure 2. HiQ 1 layout.

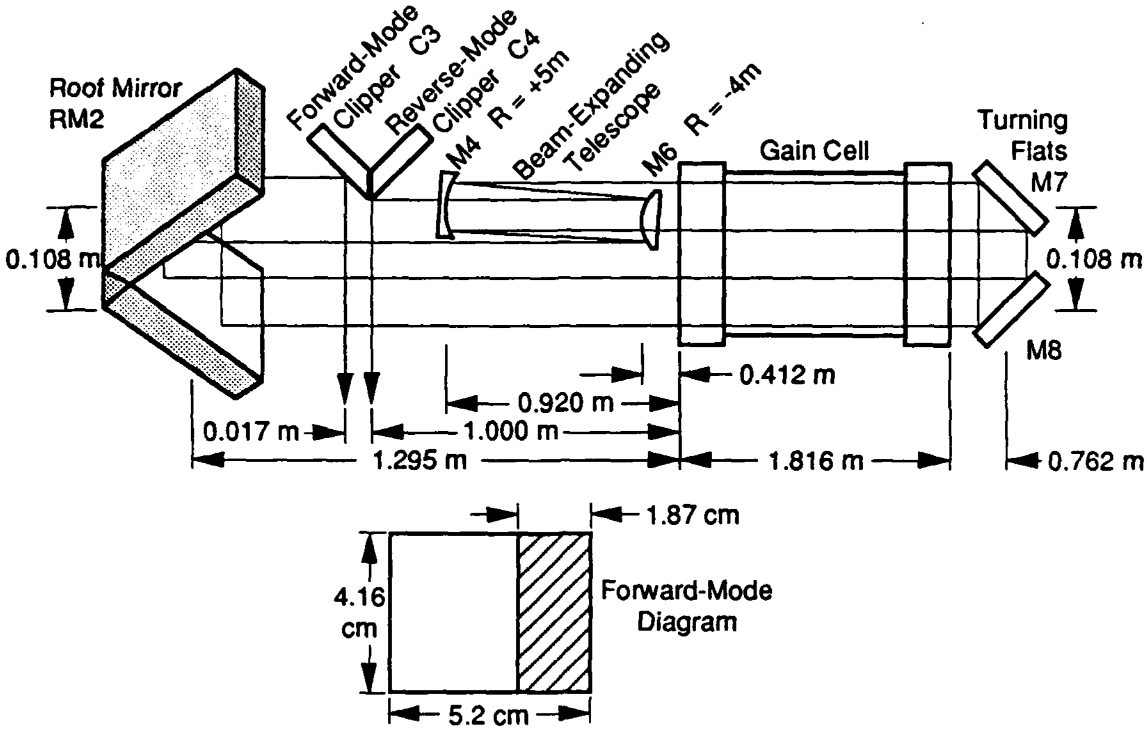


Figure 3. HiQ 2 layout.

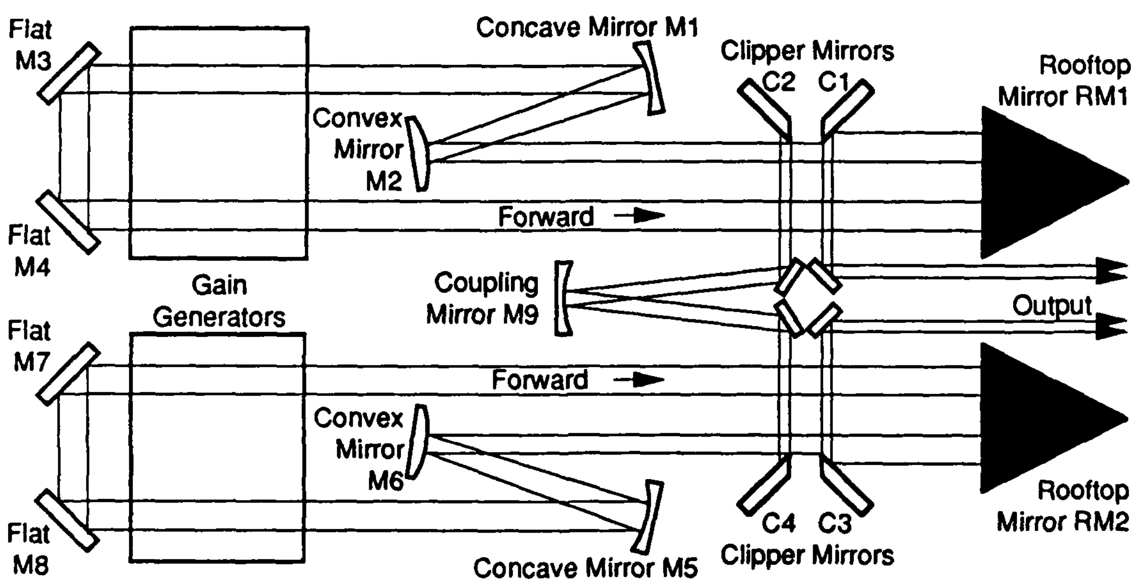


Figure 4. Phase-locked system.

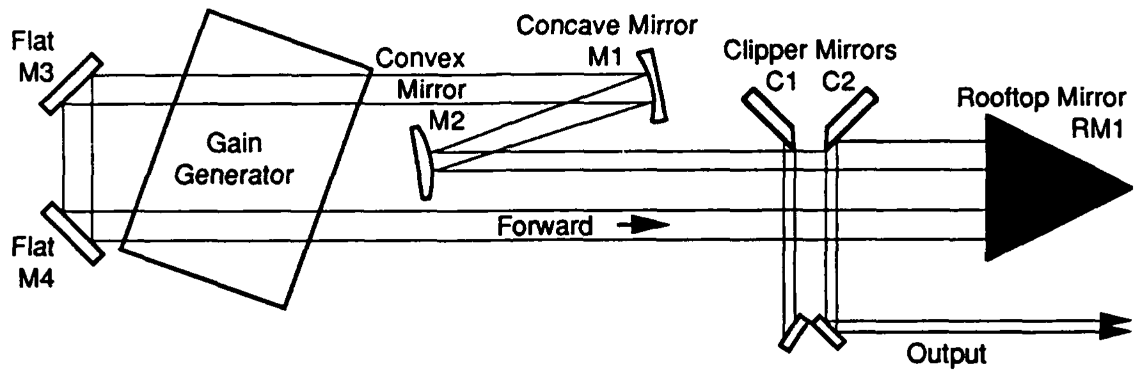


Figure 5. Skewed gain generator.

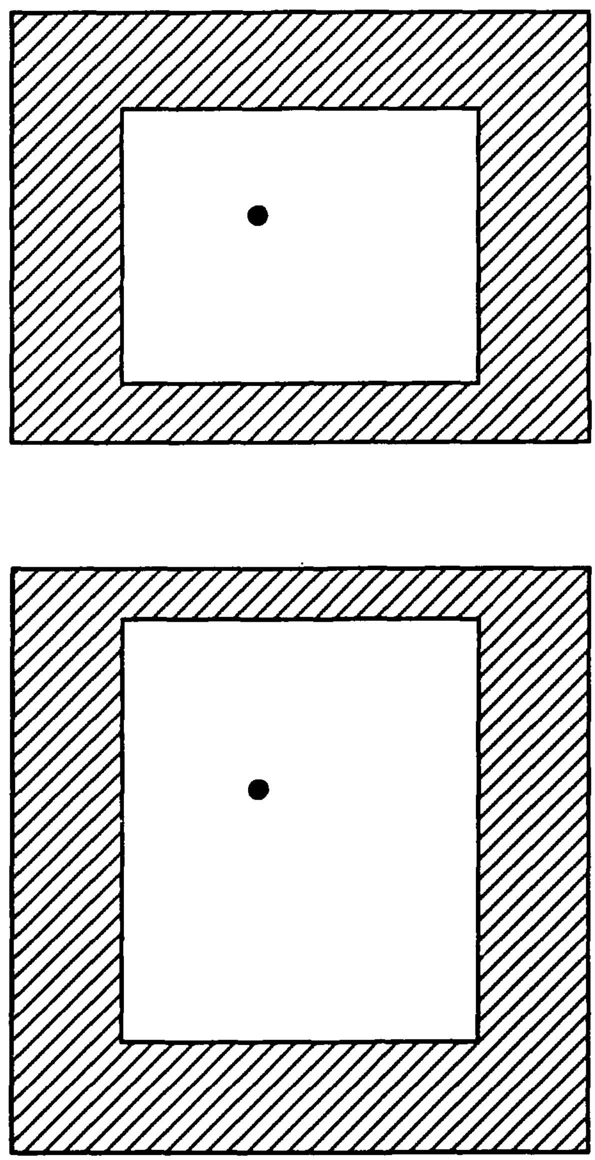
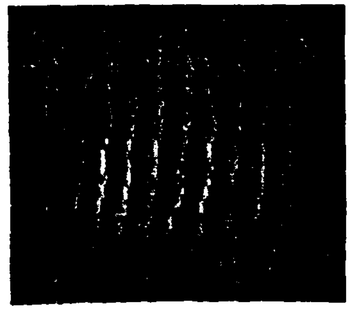
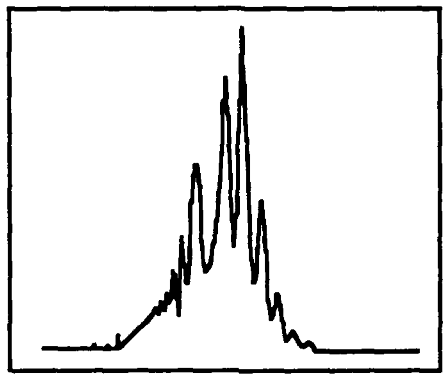


Figure 6. Masks and beam size. (Shaded areas represent masks, inner squares the beams, and dots the locations of the optical axis.)



(a) Fringe pattern.



(b) Fringe profile.

Figure 7. Fringes.

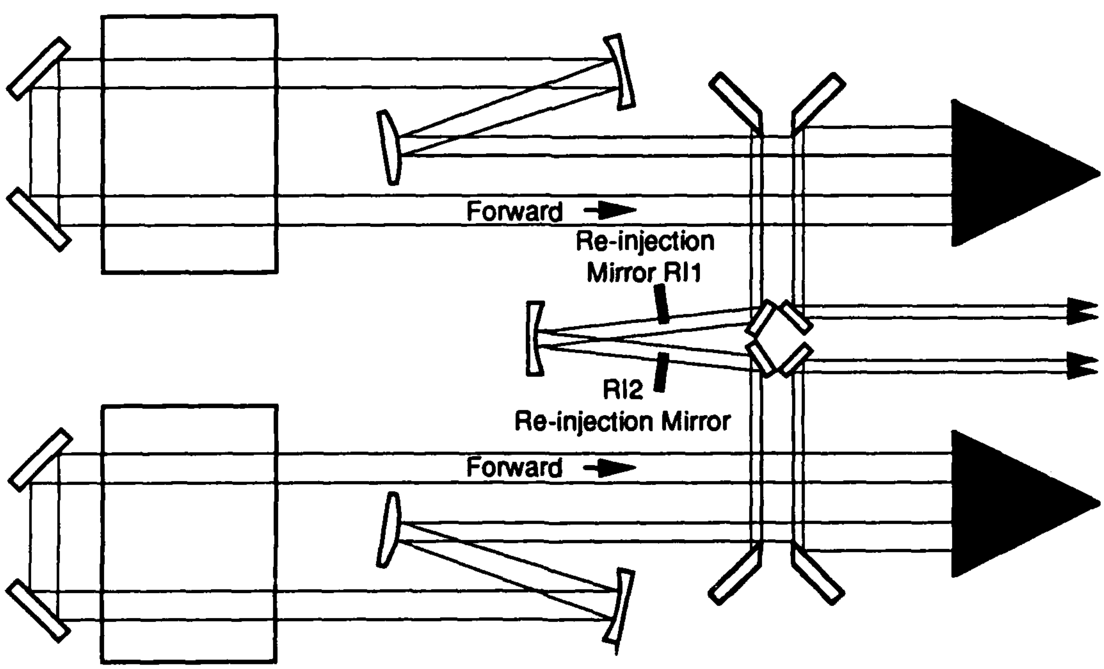


Figure 8. Location of injection mirrors.

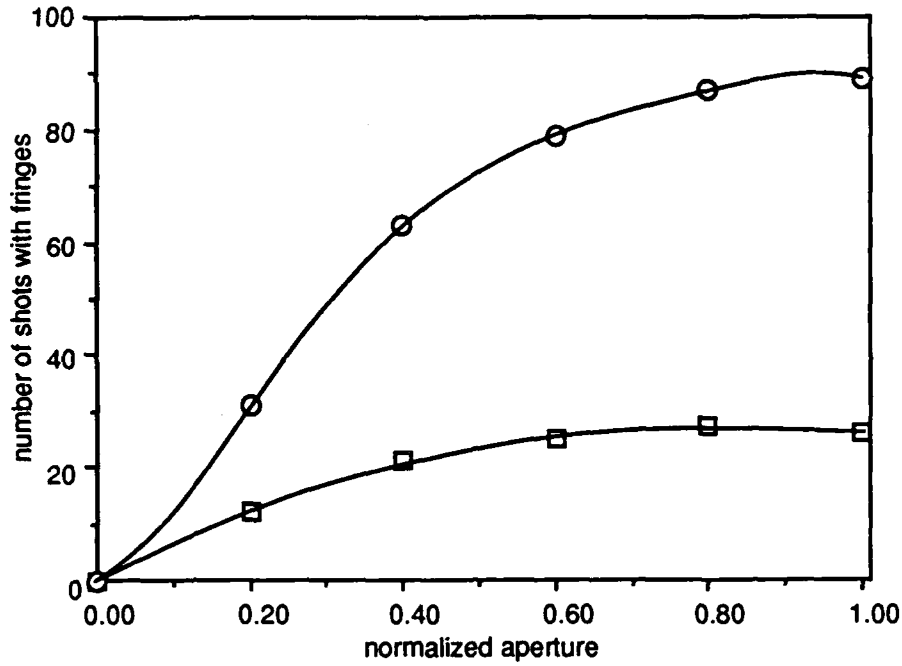


Figure 9. Number of fringes as function of aperture size. (Counter: Individual A. O represents count with the injection mirror in place. □ represents count with the injector mirror blocked.)

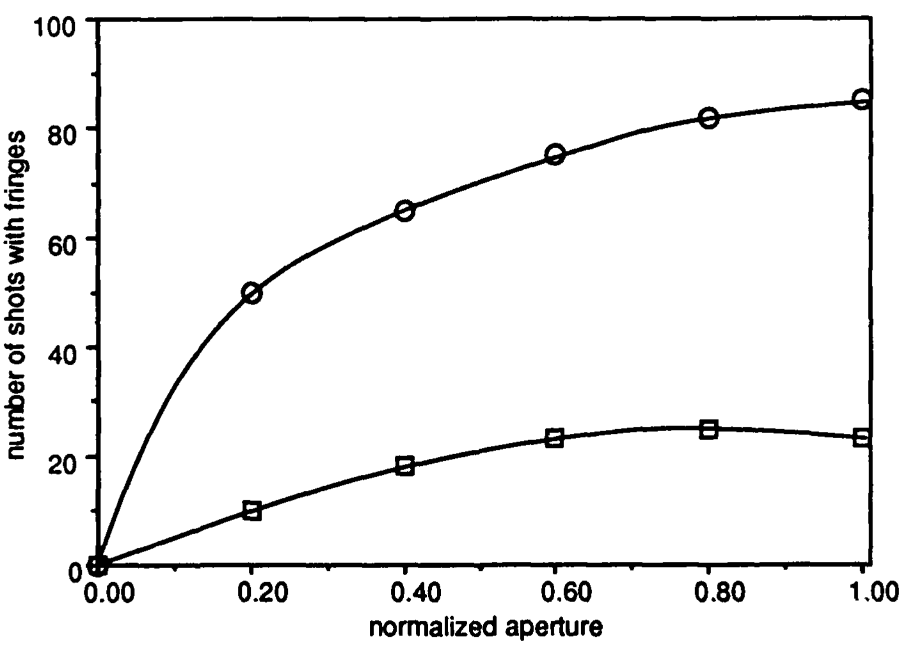


Figure 10. Number of fringes as function of aperture size. (Counter: Individual B. O represents count with the injection mirror in place. □ represents count with the injector mirror blocked.)

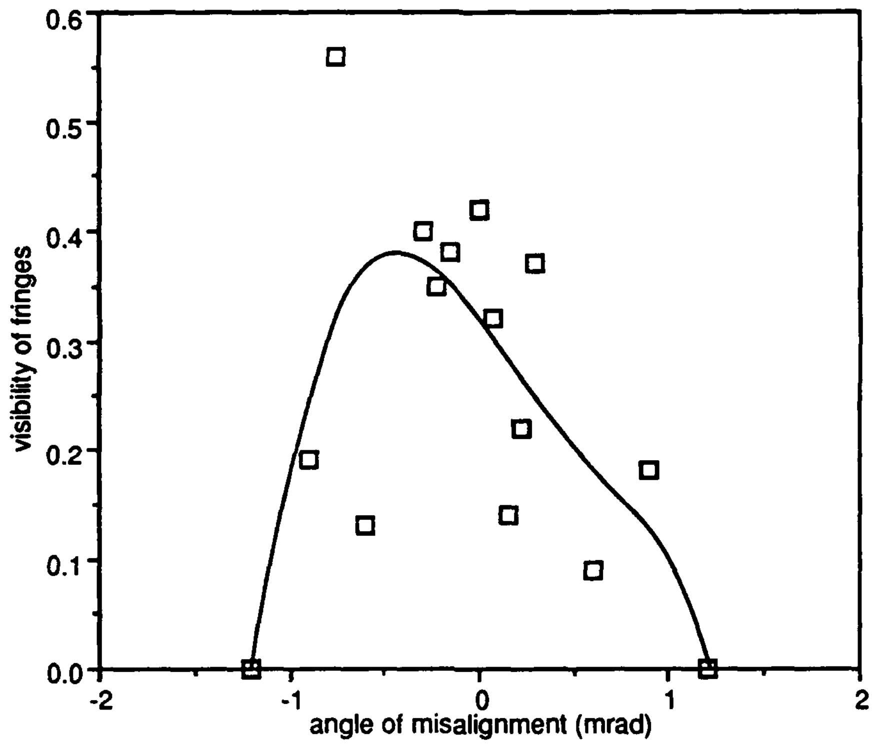


Figure 11. Misalignment sensitivity.